FEA analysis of the adaptive mirror design for the European XFEL beam transport

Presenting author: Fan Yang
Organisation: European XFEL GmbH

Corresponding author: Fan Yang
Organisation: European XFEL GmbH
Email: fan.yang@xfel.eu

Co-author(s): Harald Sinn[1], Antje Trapp[1], Riccardo Signorato[2], Tino Noll [3]
Organisation: European XFEL GmbH [1]
Bruker-ASC GmbH [2]
Helmholtz Zentrum Berlin, BESSY-II [3]

Theme: mechanical design and FEM analysis for the adaptive mirror

Abstract:

In the beam transport system of the European XFEL, an offset and distribution mirror scheme is designed using adaptive piezoelectric bimorph technology. There will be in total eleven mirrors planned over all the 3 beamlines, SASE1, SASE2 and SASE3. For the first and second mirrors in these three beamlines, especially for SASE3, the spontaneous radiation is considered as the critical heat load on the mirrors. Moreover, the different experiments and the quality of the XFEL beam require that the shape error of the mirror should be at the unprecedented level of better than 2nm peak-to-valley over 700mm optical length, with the focusing curvature continuously tunable between an ideal flat and 50km spherical radius [1]. To fulfill all these extremely stringent requirements under the expected heat load, a bimorph mirror based on a novel concept with four rows of PZT actuators attached on the four corners of the silicon substrate, and including provisions for cooling has been designed. Using the finite element tool ANSYS®, static thermal and mechanical performance of this innovative bimorph mirror are simulated in detail. Besides, the mirrors will operate in a vibration-optimized UHV chamber based on parallel kinematics, to meet the requirements on pointing stability dictated by the long distance to the experimental setups.

1- Introduction

The European XFEL is a new research facility currently under construction in the Hamburg area in Germany. From 2015 on, high intensity beams with a photon energy range from 0.5 to 12.4keV will be generated. The photon beamlines will transport X-rays from the undulator to the experimental hall along a distance of 958.2 m.

In the beam transport system, several optical devices are included, e.g. double crystal monochromators, beam power absorbers and optical mirrors etc. All these components need to be designed to sustain the extreme energy level of the beam radiation. In all the optic components, the offset and distribution mirrors are critical elements for the beam transport performance. All the mirrors, especially the 1st offset mirror which is exposed to the spontaneous radiation of 10-100W, need to be cooled. The 2nd offset mirror needs to be bendable from flat to about 10-50km, to compensate the thermal deformation of the 1st mirror, and to create an intermediate focus for the branch beamlines. In the following, the mechanical and thermal simulations for a new design of the adaptive mirrors in the European XFEL beam transport system will be presented.

2- Mechanical design and FEM analysis

After one of the first deformable bimorph mirrors with PZT actuators being installed and tested in ESRF [2,3], the sandwich-like structure with the active piezoelectric material embedded in the middle of inert polished blades has been employed in several light source facilities and showed good behavior in adaptive focusing for individual experiments [4]. However, the radiation level in the European XFEL beamlines is extremely high, so that the performance of the sandwich structure cannot fulfill the condition of the beam transport system. Therefore a new design with four rows of PZT actuators on the side of a bulk silicon substrate is developed by Thales-SESO recently [5], see Figure 1. This new design also allows, contrarily to the sandwich-like structure, to include provisions for cooling.

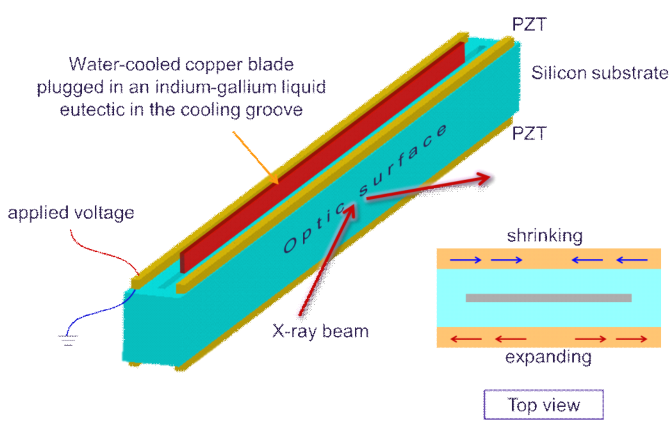

Figure 1: Initial design of the 2nd offset mirror including cooling scheme

The mirror substrate is approximately 1m long, with two grooves machined on the top and bottom surfaces. The optical surface lies in the vertical plane, as required for the horizontal sideways reflection geometry. The top groove is filled with indium-gallium eutectic with a water-cooled copper blade plunged in it. The PZT actuators near the optic surface are inversely polarized from the actuators near to the back side of the mirror, which are covered with individual electrodes on the surfaces. Therefore, applying the same electrical potential, the inverse deformation of the PZT actuators on opposite rows will cause an overall bending of the mirror substrate.

For the 1st offset mirror in SASE1, a 10W heat load due to spontaneous radiation is applied as surface load on a 3mm wide stripe on the optic surface. Figure 2 shows the model and temperature distribution of a static thermal simulation. It approved that the cooling scheme is efficient for this level of heat load, and the total bending is within the control range of the PZT actuators. Taking into account the edge effect caused by the actuators, there is at least about 30mm wide smooth zone on the optic surface.

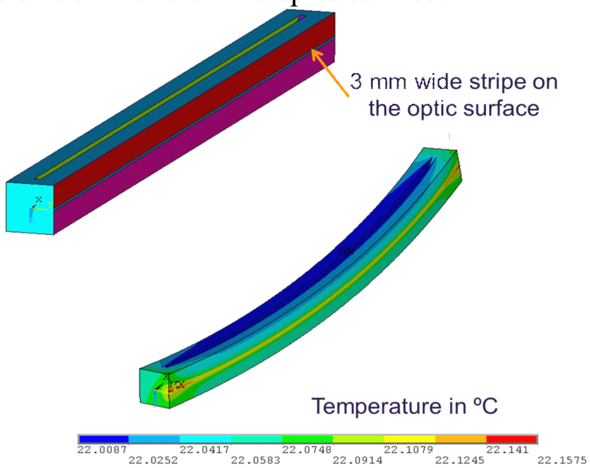

Figure 2: Temperature distribution of the 1st offset mirror (Mirror 1)

The 2nd offset mirror should be able to compensate the thermal deformation of the 1st offset mirror. Therefore the bending capability of the 2nd mirror is a critical requirement for its mechanical design. As shown in Figure 3, applying 315V of voltage homogeneously on all the electrodes, the bending of the mirror is about 56km, which fulfills the technical specification on total bending stroke required.

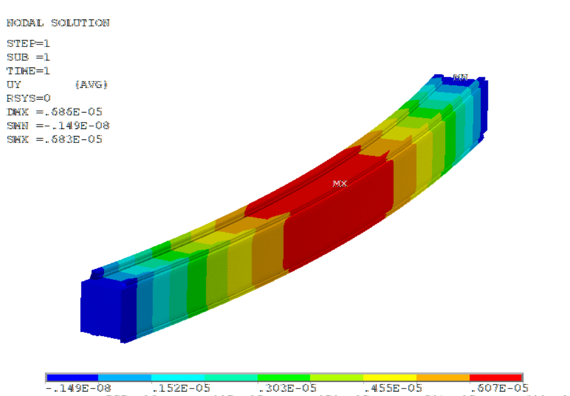

Figure 3: Bending of the 2nd offset mirror under 315 V applied voltage.

By subtracting a cylindrical shape from the total bending curve, the residual shape error obtained is plotted in Figure 4. It can ben seen that because of the mounting and supporting on the ends, the residual error in the center part is about 10nm PV when the cylindrical fit is carried out over the total length of the mirror. When fitting over 800mm in the middle region, the residual error drops to only about 2nm. If the fitting is carried out over the central 700mm length, the residual shape error PV is close to 1nm, which fulfills the technical specification on the aspect of the required shape error perfectly.

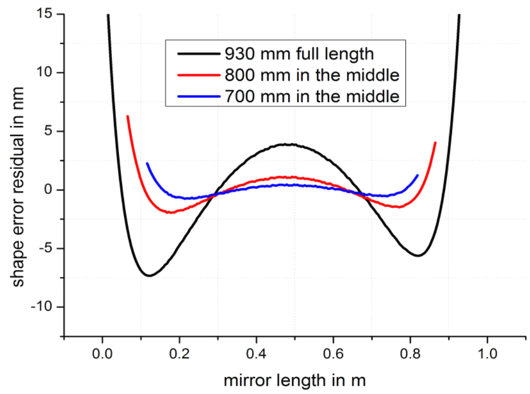

Figure 4: Bending of the 2nd offset mirror under 315 V applied voltage.

3- Control capability

One of the main advantages of the adaptive mirror is the flexibility offered by zonal deformation control. The local bending capability of the mirror substrate is related to the number of electrodes on the piezoelectric ceramics [6]. In Table 1, it is assumed that 18 electrodes are attached to the surface of each PZT row. A voltage of 315V is applied sequentially to the electrodes in 7 modes. In Figure 5, the plots show the deflection induced in mode 1-6. Subtracting the deformation of mode N from mode N+1, the local bending due to every two electrodes is also plotted in Figure 5. If the voltage is applied alternately on the electrodes, the high frequency oscillation is plotted as Mode 7, which shows the minimum limit of local bending capacity of the active mirror, see Figure 6. In a first order approximation, the deflection is linearly dependent on the applied electric voltage.

	Electrodes 1-18 on each row of piezo actuator																	
mode	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	V	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	V	V	V	V	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	V	V	V	V	V	V	0	0	0	0	0	0	0	0	0	0	0	0
4	V	V	V	V	V	V	V	V	0	0	0	0	0	0	0	0	0	0
5	V	V	V	V	V	V	V	V	V	0	0	0	0	0	0	0	0	0
6	V	V	V	V	V	V	V	V	V	V	0	0	0	0	0	0	0	0
7	V	-V	V	-V	V	-V	V	-V	V	-V	V	-V	V	-V	V	-V	V	-V

Table 1: Pluse function demonstrating the local bending with V=315V

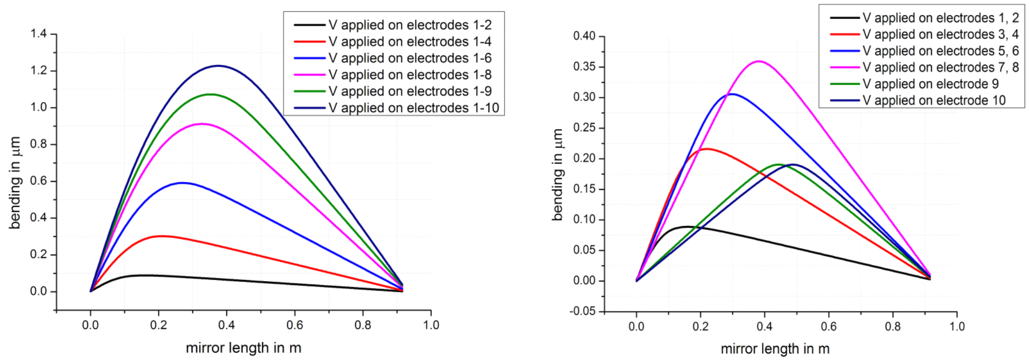

Figure 5: Deflection with 315V in mode. Left: overall deformation. Right: influence (pulse) functions associated to various combinations of electrodes

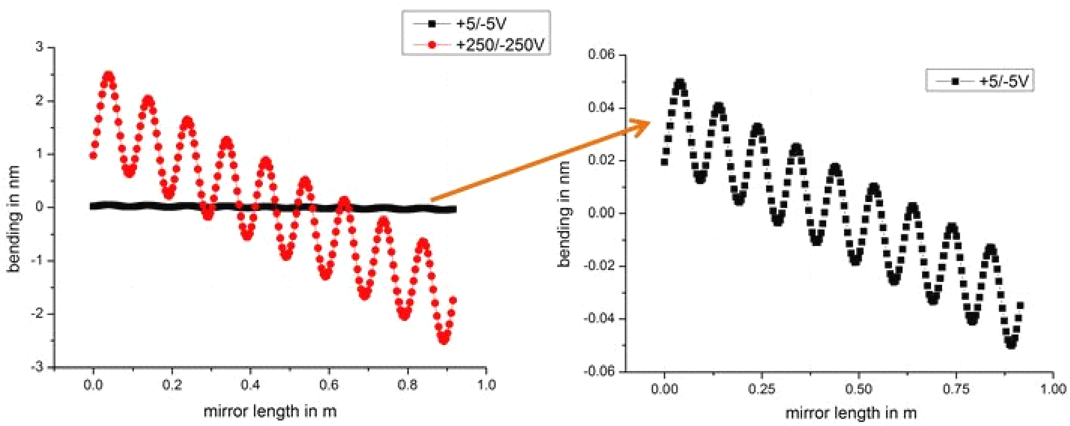

Figure 6: Deflection of mode 7, sinusoidal voltage of ±5V and ±250V applied

4- Mirror chamber

The mirror chamber should be able to hold and steer the mirror precisely. To perform these motions with a maximum stiffness, the scheme of Cartesian Parallel Kinematic motion was adopted in collaboration with HZB/BESSY. By means of FEA simulations the shape and the structure was optimized so that the eigenfrequencies of the chamber are above 90Hz. Furthermore, the UHV environment of the mirror chamber should fulfill the vacuum specification to ensure the motion of the active mirror. The deformation due to the vacuum force is up to 100micrometers. Therefore an interferometric measurement is needed to characterize the deformation of the mirror chamber. For the final design, a support of granite was chosen to optimize the vibration properties, see Figure 7.

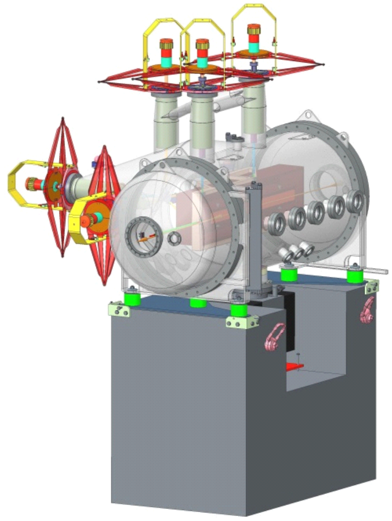

Figure 7: Mirror chamber design

5- Summary

A newly designed adaptive mirror developed for the European XFEL is based on an innovative design [5] that makes use of 4 rows of PZT actuators attached outside of the mirror substrate. By means of FEM analysis, the thermal and mechanical deformations, shape measurement and deflection control were thoroughly characterized, by analysing and optimizing their dependence on the geometry and material properties of the mirror substrate, piezoelectric actuator and the assembly process. The prototype of the mirror with the mirror chamber will be built in 2013 and the functional behavior will be investigated.

References

[1] Sinn, H. et al., CDR for X-ray optics and beam transport, (2012), xfel.eu.

[2] J. Susini, D. Labergerie, O. Hignette, R&D program on bimorph mirros at the ESRF, SPIE Vol. 2856 (1996), 130-144.

[3] R. Signorato, Multi-segmented piezoelectric mirrors as active/adaptive optics components, SRI'97 (1997).

[4] H. Nakamori, S. Matsuyama, S. Imai, T. Kimura, Y. Sano et al., Experimental and simulation study of undesirableshort-period deformation in piezoelectric deformable x-ray mirros, Rev. Sci. Imstrum. 83, 053701 (2012).

[5] Patent owned by Thales-SESO, deposited in France on Feb. 2011, reference number 1000471.

[6] K. J.S. Sawhney, S. G. Alcock, R. Signorato, A novel adaptive bimorph focusing mirror and wavefront corrector with sub-nanometre dynamical figure control, Proc. SPIE 7803, Adaptive X-Ray Optics, (2010), 1-9.